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INSTITUTE FOR DEFENSE ANALYSES

FCS Vehicle Transportability, Survivability, and Reliability Analysis

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PREFACE

This document was prepared for the Office of the Secretary of Defense, Program Analysis and Evaluation, under a task titled “Technical Analyses for Army and Marine Corps/SOCOM Systems.”

CONTENTS

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Science and Technology Division

I. IDA Summary: Future Combat System Unit of Action and Vehicle Transportability

Science and Technology Division

IDA Summary: Future Combat System Unit of Action and Vehicle Transportability

- C-130 Transportability—a design *constraint*.
  - Vehicle design is at "edge" of C-130 compatibility.
  - Transportability not significantly improved.
    - Intra-theater:
      - C-130 use limited in realistic conditions.
      - Combined sea/land transport often faster.
    - Inter-theater:
      - Air Transportability (in C-17s) of Unit of Action is cube limited for vehicles less than 35 short tons; vehicle weight is irrelevant in this region.
- Vulnerability to medium-caliber kinetic-energy weapons is increased by C-130 constrained vehicle weight.
- Therefore:
  - For C-130 transportability, design to 11–14 tons.
  - A 20-ton vehicle is not usefully transportable and imposes substantial design compromises on survivability.
- Army Comment: [This is a] "Significant Observation."

C-130 transportability functions as a design constraint for the Future Combat System family of vehicles, one that puts absolute limits on the weight (less than 20 short tons, 1 short ton = 2,000 pounds) and similarly stringent constraints on length, width, and height.[1] Yet the choice of 20 short tons as the vehicle weight does not improve the vehicle transportability except under the most favorable conditions. Moreover, the need to be survivable drives the Future Combat System vehicles toward weights that are much larger than the 20 short ton limit. Thus, the vehicle weight choice should be much lower than 20 short tons to satisfy compatibility or much higher than 20 short tons to make the vehicles more survivable. Either choice obviates the artificial constraint imposed by C-130 transportability.

1 Joseph F. Cassidy, “C-130 Transportability of Army Vehicles,” MTMCTEA (MTTE–DPE), 15 March 2001.

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IDA Summary: Sustainability/Reliability

- The Future Combat System Family of Systems must maximize available combat power while achieving significant logistics footprint reductions and personnel efficiencies in the area of operations through reduced demand for maintenance and supply.
- We looked at some cornerstone enabling capabilities:
  - Operational Availability
    - High reliability is a derived requirement, and achieving it will be difficult.
    - Additional methods to improve operational availability should be pursued.
      - Reducing administrative logistic delay time, the use of prognostics (a critical technology), and periodic replacement of all critical parts.
  - On-Board Water Generation
    - Distribution of generated water on the battlefield is largely unaddressed.
      - Logistics impact of water generation unclear.
    - It is not clear why on-board water generation is urgent—or a critical technology.
      - Water generation equipment package is likely to be traded for weight savings, especially if the C-130 requirement remains.

Why are prognostics and water generation important enabling capabilities for sustainability and reliability?

Sustainability/Reliability—Key Performance Parameter 5 (KPP5)

We looked closely at operational availability, an enabler of reliability, and water generation, and enabler of sustainability.

Operational availability (Ao) is defined mathematically as (vehicle up time) / (vehicle up time + vehicle down time); it is meant to convey the fraction of time the vehicle is available for combat operations. The Future Combat System Key Performance Parameter for Reliability/Sustainability states that operational availability should be 99% (objective) and 85% (threshold). The Operational Requirements Document specifies a 95% operational availability. To reach those operational availability values, the developers are attempting to build vehicles that are highly reliable, that is, vehicles that have long mean time before system abort (MTBSA).

- For example, simulations and analysis have shown that to achieve an Ao of 95% with the Future Combat System Infantry Carrier Vehicle, an MTBSA of approximately 1,300 hours is needed.
- To date, the average measured MTBSA for a sampling of current vehicles:[2]

Vehicle	MTBSA (hours)
Stryker Infantry Carrier	167
Bradley	133
Abrams	27

These MTBSA values for the Stryker and Bradley are approximately 1/10th of what is needed for the Future Combat System Infantry Carrier Vehicle.

2 *Systems Engineering Review*, *Future Combat System*, OUSD/ATL, 11 April 2003.

- United Defence and General Defence, the contractors for the Future Combat System who are building the Infantry Carrier Vehicle, have agreed to build an Infantry Carrier Vehicle with an MTBSA of about 500 hours. That is still less than half of what is needed to meet the requirement.

Although it is theoretically possible to increase reliability by an order of magnitude, considering the complexity of the vehicles, the risks are very high. If the administrative logistic delay time, the time it takes to deliver the parts plus the time it takes to repair the vehicle, can be reduced, operational availability can be increased substantially. In principle this could be done without having to increase the vehicle reliability.

The use of prognostics—monitoring critical parts and predicting when breakdown is imminent—can potentially increase operational availability. This allows for timely ordering and replacement of parts and will most likely reduce the time in the shop, assuming that a part can be replaced before it breaks down faster than it can be repaired. Statistical prognostics can also be applied. This is monitoring the frequency with which parts commonly break down, then making sure that those parts and proper tools are in stock. (We do not specifically address this type of prognostics in this briefing, aside from noting that it is a method that should already be in use and aimed at administrative logistic delay time.)

II. Transportability and Survivability

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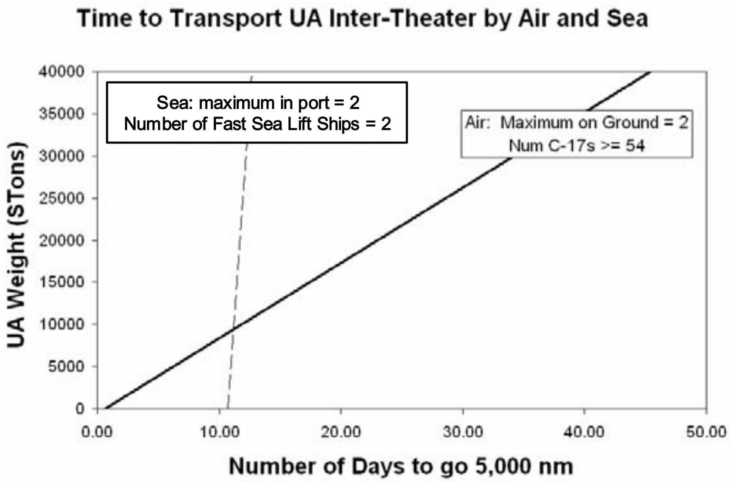
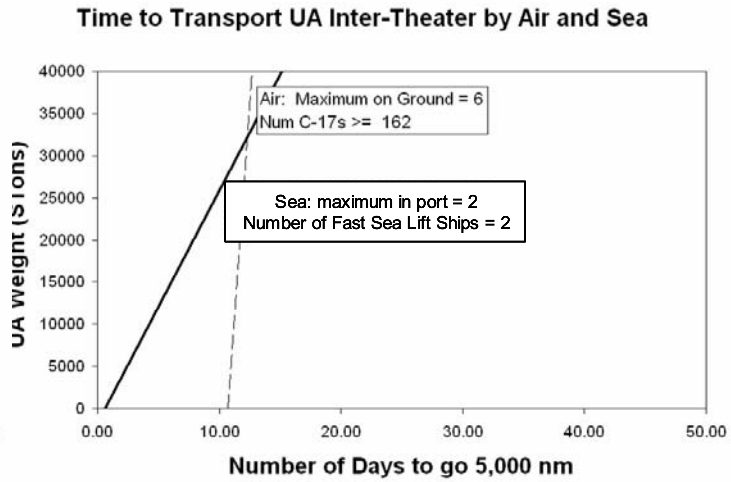
Unit of Action Inter-Theater Transportability





Important Parameters:		
Unit of Action and Combat Support Area	225,000	ft^2
Unit of Action and Combat Support Weight	40,000	Stons
Average Aircraft Payload	55	Stons
Average Ship Payload	20,000	Stons
Transport Distance	5,000	Nmile
Ship Speed	24	knots
Aircraft Speed	350	knots
Load/unload and refueling times are included		

- Low MOG airports limit the air delivery time.
- But, for high MOG airports, the limitation on air delivery is the total weight.
- Delivery by sea compares favorably with air delivery in nearly all cases.

Background

The analysis compares transportability of the Unit of Action by sea and air. We consider two secnarios: (1) a realistic scenario in which the maximum number of aircraft on the ground (MOG) equals 2 (upper left chart) and (2) a scenario in which the MOG equals 6 (upper right chart). The second scenario is unlikely to be achievable in situations when the troops are delivered to enemy territory. We considered the second scenario here only to explore under which conditions sea and air delivery times are comparable for inter-theater distances, in this case 5,000 nmi.

Model Parameters

The input parameters for calculations are assumed to be the same as those used at the Office of the Secretary of Defense, Program Analysis and Evaluation, Simulation and Analysis Center; they are given in the table. The strategic sealift consists of two Fast Sealift Ships; the C-17 is used for airlift. It is assumed that a C-17 will fly 10 hours per day (C-17 contingency utilization rate is 11.7 hours).[3] It is assumed that the air destination points are at the intended action location. However, while the sea destination points are close, they are not at the final action location. The vehicles will need to drive 200 miles to get to the fight. The estimated drive time, 4 days, is included in the time to deliver the Unit of Action.

Description of Results

Delivery by sea is limited by the speed of the ship. Loading and unloading times are small compared with the time it takes to arrive to the destination point. Delivery by air is limited by the aircraft payload, unloading rate, and MOG, since these parameters control how much materiel can be unloaded at the airport per unit time. Assuming that a sufficient number of aircraft are available, for a given aircraft (i.e., fixed speed, average payload, and unloading time), MOG is the controlling transportability parameter. Examples of airfields with low MOG (~2) are Kandahar, Afghanistan, and Mogadishu, Somalia.[4] Examples of high MOG airfields (~8) are the U.S. bases in Germany and Saudi Arabia. But, the issue of “hot load with

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3 Air Force Pamphlet 10-1403, “Air Mobility Planning Factors,” 1 March 1998.

4 “SBCT Mobility Analysis,” by PA&E, 11 March 2003.

ammunition" would likely limit the MOG (because unloading planes holding vehicles carrying live ammunition takes longer), so the base in Ramstein, Germany, which has an MOG of 1–2, is fairly typical.[5]

1. MOG = 2

It is common (and realistic, if not optimistic) to use an MOG of 2 as a reasonable number for a scenario in which the troops are delivered into a hostile territory. As can be seen from the figure, delivering relatively large loads by sea takes considerably less time than delivery by air. For small loads (around 10,000 short tons), the air and sea delivery times are comparable.

2. MOG = 6

As MOG is increased from 2 to 6, air and sea delivery times are comparable in terms of number of days to deliver 35,000–40,000 short tons. For a delivery weight around 20,000 short tons (the estimated weight of the Unit of Action is slightly greater than 16,000 short tons), air delivery is superior to sea. But to accommodate such a high MOG, unloading rates, and the 5,000 nmi distance, the number of C-17s required is almost 170, which exceeds total capacity of U.S. Air Force of 120.[6]

Conclusion

- Under realistic conditions—delivery over 20,000 short tons and MOG not greater than 2—strategic lift for distances on the order of 5,000 nmi by sea is preferable to delivery by air.
- Only for high MOG (in this case 6) is air delivery competitive with sea delivery for loads of 30,000 short tons or less. In this case, however, the amount of aircraft required exceeds the total U.S. Air Force inventory.

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5 *The U.S. Army and the New National Security Strategy*, ed. Lynn E. Davis and Jeremy Shapiro (Santa Monica, Calif.: RAND, 2003).

6 Research paper by Maj. Randall Long, Air Command and Staff College, AU/ACSC/0265/97-03.

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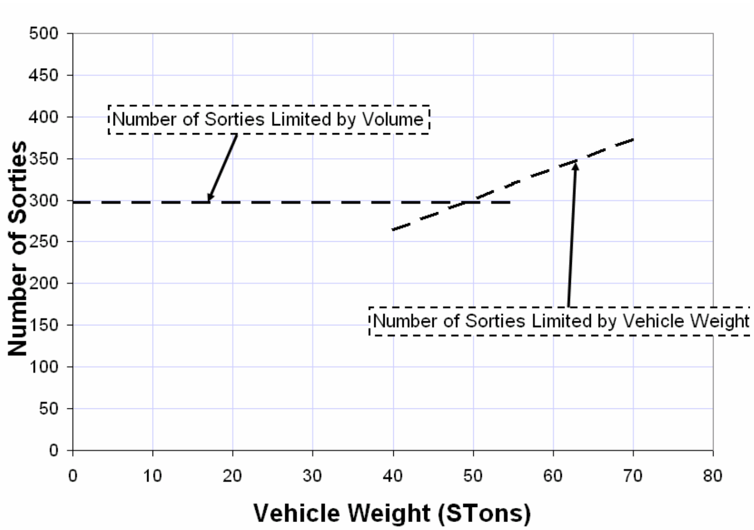
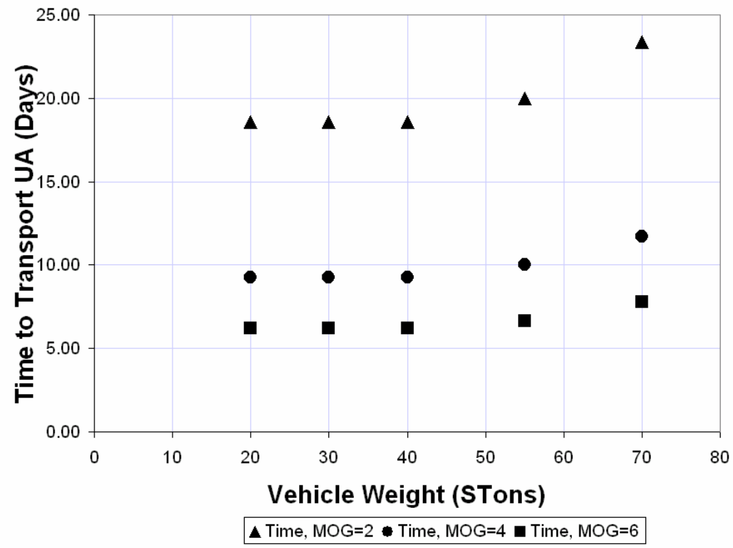
Vehicle Weight and Transportability





Number of C17 sorties/MOG/Day	8	
Total UA Weight for 20 STon Vehicle	16,100	Stons
Number of UA Vehicles	306	
FCS Vehicle Weight	20	Stons
C17 Average Payload	55	Stons
Max C17 Payload	84	Stons

Minimum number of C-17 sorties is 297. Number of vehicles in Unit of Action stays constant. Vehicle weight varies.

Strategic transportability is unaffected by vehicle weights below about 45 short tons.

The analysis explores how the vehicle weight in the Unit of Action affects transportability in terms of total number of sorties and days. We assume that the maximum vehicle weight is 20 short tons. The left chart demonstrates that the number of sorties required will be unaffected by the vehicle weight up to about 45 short tons. This is a straightforward consequence of the fact that for light vehicles, moving a brigade is volume limited, not weight limited, when flown by C-17. In this region the number of sorties is controlled by the average payload weight of the aircraft. (The parameters for the calculations are given in the table.) Further increase in vehicle weight beyond around 45 short tons leads to a linear increase in the required number of sorties.

The chart on the right shows how the vehicle weight affects the number of days needed to transport the Unit of Action composed of 20 short ton vehicles for three different MOGs. These calculations show that the increase in the vehicle weight up to about 45 short tons does not have a significant effect on C-17 delivery times.

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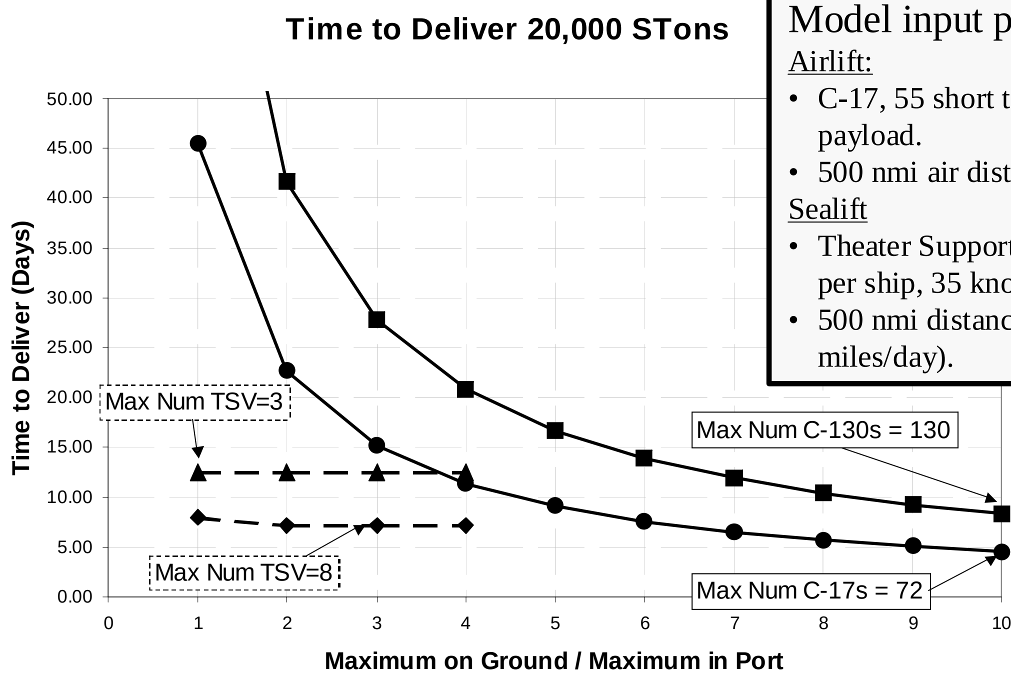
Intra-theater Unit of Action Transportability Options



Model input parameters:

Airlift:

- C-17, 55 short ton payload; C-130, 20 short ton payload.
- 500 nmi air distance.

Sealift

- Theater Support Vessel, 1,250 short ton payload per ship, 35 knots.
- 500 nmi distance and a 200 mile drive (50 miles/day).

Unit of Action air delivery time is limited by MOG. Sealift is faster if airport MOG is less than 4.

The chart summarizes results that address the question of under what conditions it is possible to transport the Unit of Action in 4 days, which was originally specified in the transportability Key Performance Parameter. This Key Performance Parameter was for inter-theater transport. Hence we show that even intra-theater transport in 4 days is unrealistic.

Several conclusions are apparent from the chart:

- It is practically impossible to use C-130 to deliver 20,000 short tons in 4 days. In fact, even for unrealistically large MOG numbers (i.e., 8 and higher), it could take at least 10 days.
- Delivery by C-17 reduces number of days needed. To reach 4 days, however, the required MOG is above 10, which is unrealistic in the scenario of delivering troops to the enemy territory. It should be noted that for the C-17, typical loading was used, but for the C-130, maximum loading was assumed.
- Sea delivery by Theater Support Vessel (TSV) is preferable to air delivery for distances of 500 nmi and for all practical MOGs. In calculating the times of sea delivery, the maximum number of vessels in port was used analogously to MOG.

Although the TSV is a proposed system, there currently exists the TSV-Interim, which is a critical step toward the definition and acquisition of the future TSV. Recent TSV interim program activities included the fiscal year 2001 contract award for an Army/Navy joint lease of HSV-X1 (*Joint Venture*) high-speed vessel. The vehicle spent 14 months in the Persian Gulf supporting Operations Enduring and Iraqi Freedom in 2002 to 2003.[7] Together with TSV-1X (*Spearhead*), the platforms are part of a TSV-Interim program of investigation and experimentation and Office of the Secretary of Defense-approved advanced concepts technology demonstration.[8]

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7 http://www.usawoa.org/TSV-1X.htm.

8 http://www.ausa.org/pdfdocs/GB/Artillery.pdf.

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Transportability—Aero limits

Lift is proportional to air density (ρ) :

- $\rho(h,T) = \rho(\text{sea level}, T_0)*e^{-(h/L)}*T_0/T$,
  - h = altitude (m)
  - T = air temperature at a given altitude (deg K)
  - T_0 = 288.15 K, the sea level standard temperature
  - L = 11,000 m, altitude of the troposphere
- "High hot" density is about 80% of Air Force standard.
  - Lift/gross takeoff weight reduced to 80%.
  - For 40,000 lb cargo, usable fuel is 4% of gross takeoff weight.

Performance under Army "high-hot" conditions is greatly reduced from Air Force standard conditions.

Thus far we have looked at what limits transporting brigade-size units in terms of the nominal performance of a fleet of aircraft and the capacity of airports to be used. We now consider moving a single vehicle in an aircraft. For this purpose we will look at a variety of real-world operating conditions, not just nominal performance.

Aircraft, unlike ground platforms, show considerable sensitivity to environmental factors. With adequate engine cooling, a typical truck's maximum load is independent of temperature over a wide range and likely to be unaffected by altitude until several thousand feet. The load is ultimately supported by the road. For an aircraft, the load is supported by the air—or by aerodynamic lift. This is dramatically affected, even by relatively small changes in temperature or altitude.

Thus, the limits on takeoff and much of the flight envelope are dominated by available lift. The effect of atmospheric conditions on lift is well understood: For a given lifting surface and velocity, lift is proportional to fluid density. How the density of air varies with temperature and altitude is also well understood and given in the equation above. This relation allows us to scale performance, in particular takeoff weight, as temperature and altitude change. We checked this scaling by looking at the three-engine climb limits and found that lift limits as modeled above give a good explanation of the trends with temperature and altitude.[9]

A change in conditions from Air Force/Federal Aviation Administration standard conditions (sea level, 59 °F) to Army high hot (4,000 ft, 95 °F) results in a lift (or gross takeoff weight) reduction of 20%. For 20 short tons of cargo, the C-130 has very little fuel (3.2 short tons) available at the 77.5 short tons (155,000 lb) maximum takeoff weight. Therefore, small percentage changes in atmospheric density have large effects on range. At high-hot conditions, gross takeoff weight is reduced by 15 short tons (30,000 lbs), which is much more than the fuel available with a 20 short ton payload.

At approximately 1,100 ft altitude (for 59 °F) or 81 °F temperature (at sea level), the lift limits on takeoff weight will prohibit flight with a 20 short ton cargo.

9 Flight Manual, USAF Series C-130 Airplanes, Technical Order 1C-130H-1-1.

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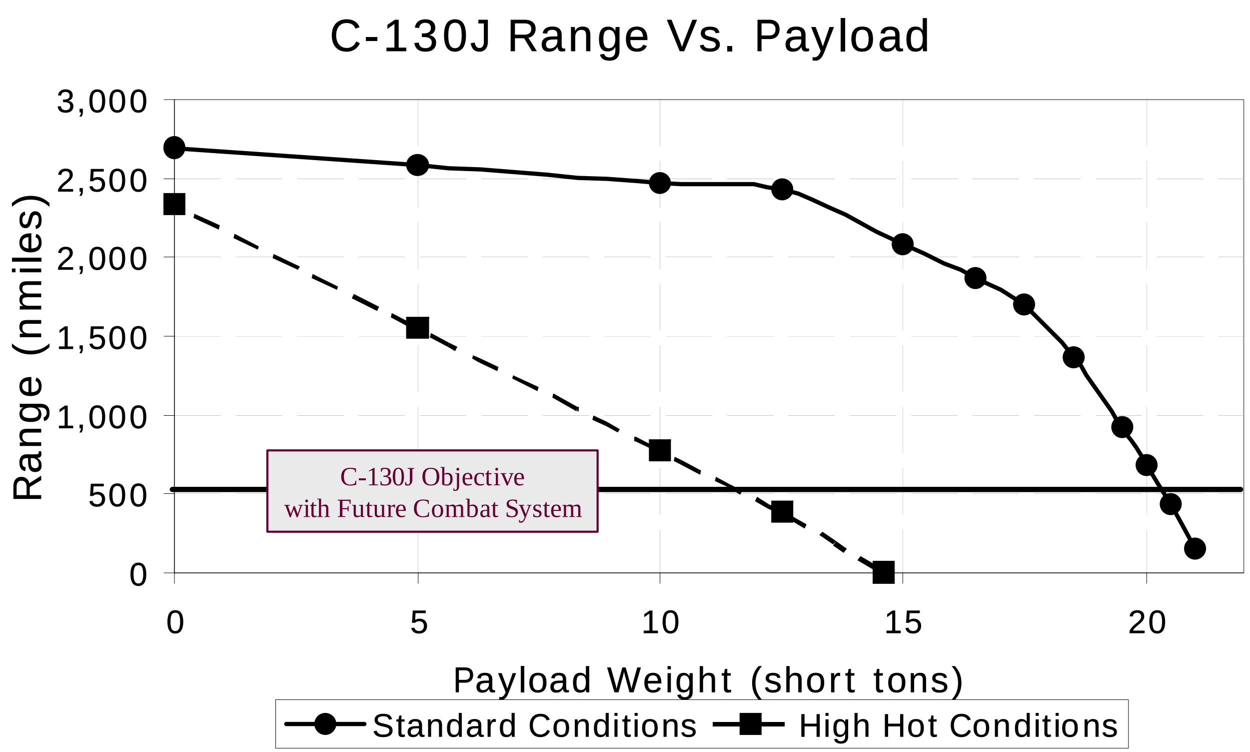
Anticipated Range for C-130J



Objective range achieved only for vehicles lighter than ~12 short tons.

This chart presents our estimated range payload curves for the C-130J (standard, *not* elongated, version) to take off under Air Force/commercial standard conditions (sea level, 59 °F) and for the Army high-hot (4,000 ft., 95 °F) conditions. The maximum takeoff weight is much lower under high-hot conditions (about 125,000 lbs) than under Air Force standard conditions (155,000 lbs). This reduction in takeoff weight limits available fuel. The nearly straight-line relation for high-hot conditions is easy to understand: The fuel available increases linearly as payload decreases. The horizontal line at 500 nmi represents the Future Combat System Family of Systems threshold requirement for minimum transport distance by C-130 and C-17 profile aircraft.

Under standard conditions and with a payload weight of up to 12 short tons, the fuel tanks can be filled to maximum, so the range only falls slightly with increased payload. At a payload weight of 12 short tons, the maximum total takeoff weight of the aircraft plus payload plus fuel has been met. Thus, for payload weights from 12 to 17 short tons, the fuel tanks cannot be filled to capacity because the added payload weight has to be compensated with a corresponding reduction in fuel weight. In this region the curve is approximately parallel to the high-hot curve. Beyond 17 short tons payload, wing-relief fuel is needed. This is fuel that must be kept in the wings to maintain their structural integrity under high loads and cannot be used in flight or during landing. Therefore, the available fuel weight decreases faster than the additional cargo weight, and the curve becomes significantly steeper.

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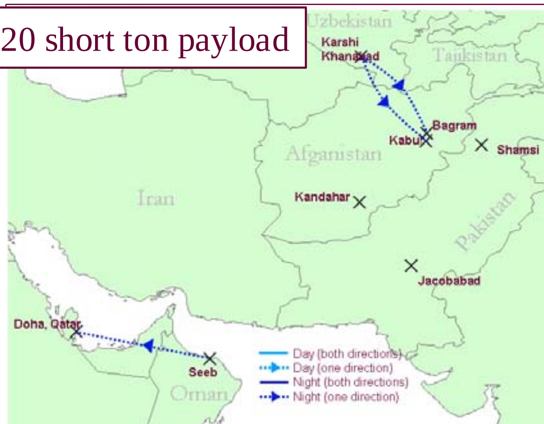
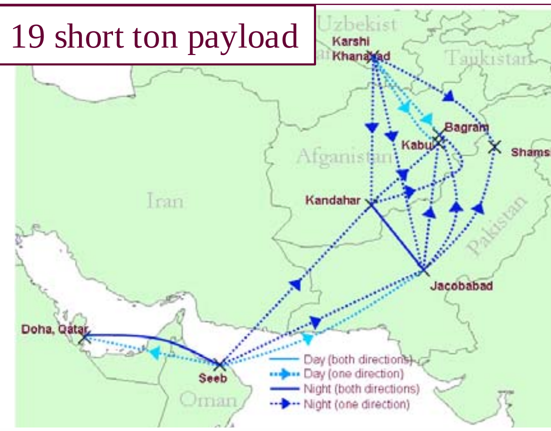
C-130 Transport in the Middle East

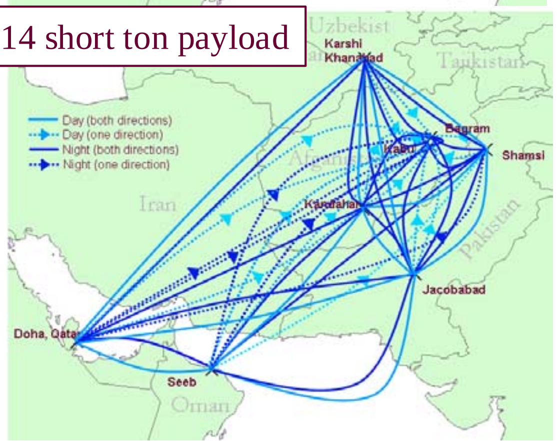
20 short ton payload

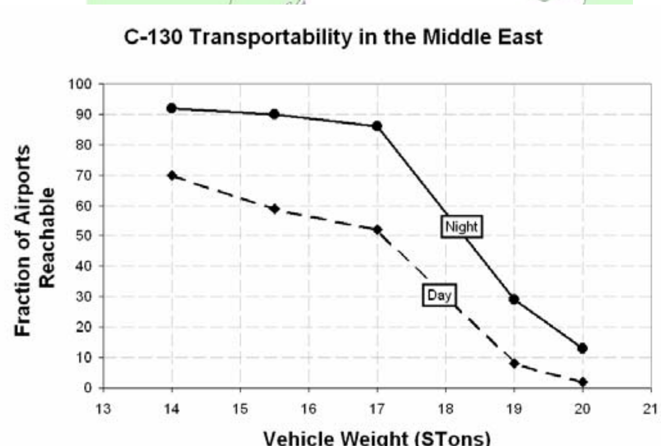


19 short ton payload



14 short ton payload





C-130 transportability is challenged for heavier vehicles.

This illustrative family of maps shows how the connectivity of airports in the greater Middle East is expanded as the payload is reduced. The gross takeoff weights and resulting ranges were generated by the Air Force and obtained through the Army by our sponsor. The curves are illustrative because notional daytime and nighttime temperatures were used. The numbers for takeoff weight agree within about 5% with standard condition performance numbers scaled with the lift model discussed above.

The plot in the lower right shows the percentage of reachable airfields in the Middle East as a function of cargo weight. The drastic decrease in transport distance at about 17 short tons and beyond occurs because of the need for wing-relief fuel. Because this fuel cannot be used, there is less total fuel available, so the transport distance decreases significantly. The distance for nighttime flights is greater than the distance for daytime flights because of lower nighttime temperatures.

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Weight Impact on Transportability

- Inter-theater airlift: Penalties at about 35 short tons or greater.
- For robust intra-theater airlift, vehicle weights should be less than
    - 12 short tons at one vehicle per C-130,
    - 35 short tons at two vehicles per C-17.

The impact of weight on transportability is gradual from 15 to 35 short tons—What about the impact on survivability?

This chart summarizes the results for how vehicle weight affects transportability. For inter-theater airlift, loads are volume limited until the combat vehicles in a Unit of Action weigh in excess of 35 tons. (There is a modest aircraft fuel-consumption effect, but otherwise, transportability is essentially unaffected by these vehicle weights.) By robust intra-theater airlift we mean that for pressure altitudes less than Army high-hot conditions, these loads can be reliably lifted from any suitable airfield.

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Vehicle Weight and Survivability

- Added armor will improve survivability
  - How does weight affect survivability against various weapons?
  - What can active protection systems contribute in lieu of conventional armor for Future Combat System vehicles?

We find large survivability improvements with increasing weight from 20 to 30 short tons. Active protection systems are unlikely to be an effective substitute.

We have shown that constraining the vehicle weight to 20 short tons does little to enhance transportability. Intuitively, reducing weight will affect survivability. Here we look at how constraining weight affects survivability against various weapons. We find that survivability decreases significantly against widely proliferated 25–40 mm kinetic-energy rounds, which are unlikely to be countered by the active protection system.

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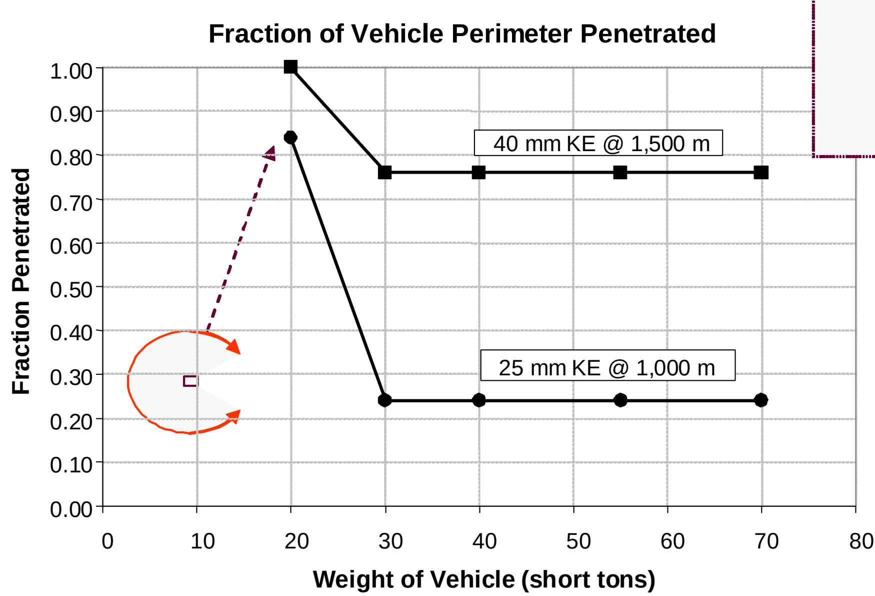
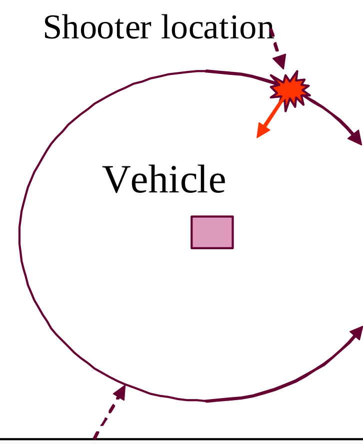
Effect of Vehicle Weight on Survivability

Vehicle weight (short tons)	Armor Thickness, mm Front	Front side	Rear side	Rear
20	55	27.5	13	13
30	130	65	65	25
40	155	80	65	25
55	260	130	65	25
70	375	190	65	25





Fraction Penetrated is computed for no overmatch; penetration depth is assumed proportional to cos(incidence angle)$^{1.5}$.*

Fraction Penetrated is the fraction of the shooter's location perimeter from which the vehicle can be penetrated.

Penetration by 25–40 mm kinetic-energy munitions drops significantly as vehicle weight increases from 20 to 30 short tons.

**Handbook on Weaponry*, 2nd English Edition (Düsseldorf: Rheinmetall GmbH, 1982).

The upper left chart demonstrates how vehicle weight affects survivability. The results are expressed by the fraction of the perimeter that is penetrated by incoming munitions. (Note that no overmatch is assumed; that is, none of the munitions pass all the way through the armor plate). Only kinetic-energy weapons are considered, since it is plausible that the protection from chemical-energy weapons by active protection systems will be achieved. The penetration depth for a given munition is taken from *Janes Ammunition Handbook*, 2003–2004; the armor thicknesses represent typical values (notional) for given vehicle weight.[10]

From these results we conclude that survivability decreases significantly as vehicle weight falls from 30 to 20 short tons. The decrease is most significant for 25 mm rounds, which are widely available.

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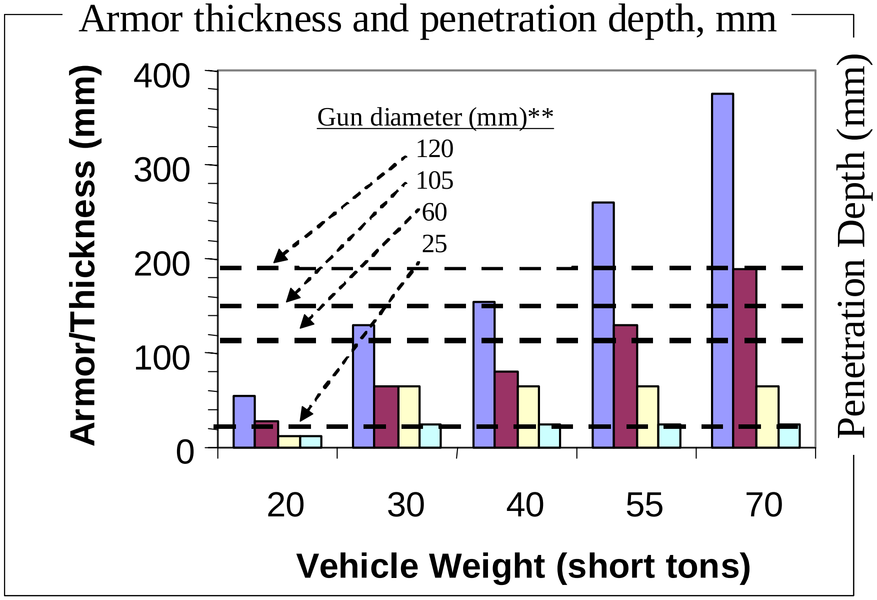
10 W. Jackson and D. Hicks, “The Effect of Engagement Range and Vehicle Weight on Survivability,” *Proceedings of the 11th Ann. Ground Target Modeling and Validation Conf.,* Michigan Tech. University, August 2000, pp. 21–36.

Effect of Vehicle Weight on Survivability



Vehicle Weight (short tons)	Armor Thickness (mm) Front	Front Side	Rear Side	Rear
20	55	27.5	13	13
30	130	65	65	25
40	155	80	65	25
55	280	130	65	25
70	375	190	65	25

Legend
- - Penetration depth
Front
Front side
Rear side
Rear

Penetration by 25 mm kinetic energy weapons drops significantly as vehicle weight increases from 20 to 30 short tons; only front sections of 55–70 short ton vehicles provide protection from 105–120 mm kinetic-energy weapons.

* W. Jackson and D. Hicks, "The Effect of Engagement Range and Vehicle Weight on Survivability," *Proceedings of the 11th Ann. Ground Target Modeling and Validation Conf.*, Michigan Tecn. University, August 2000, pp. 21–36.

** Penetration at 2,000 m distance and 60-degree incidence angle; *Janes Ammunition Handbook*, 2003–2004.

This chart gives a summary of the effect vehicle weight has on survivability. The data show that 20 short ton vehicles are protected from 25 mm weapons only from the front. Vehicles weighing from 30 to 55 short tons are able to survive frontal impact by medium-caliber weapons. Unlike lighter vehicles, heavier vehicles (in the range of 55 short tons and higher) are able to survive frontal impact by larger weapons—105 and 120 mm.

If a battle scenario is considered in which the attack can come from many directions (e.g., in an urban environment), increasing vehicle weight from 20 to 30 short tons has a significant effect on the vehicle survivability against easy-to-deploy-and-hide, medium-caliber weapons.

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Advanced Active Protection Systems

- State-of-the-art Russian active protection system arena:
  - Protects from rocket-propelled grenades and antitank guided missiles;
  - Utilizes a millimeter radar;
  - Threat speed range: **70–700 m/s;**
  - Mass: ~2,200 lb;
  - Power consumption: 1 kW.
- Future Full Spectrum Protection Close-in Shield (FCLASS)
  - Under development by U.S. Army (TARDEC);
  - Designed to provide countermeasures against rocket-propelled grenades, antitank guided missiles, and high-explosive antitank ammunition (chemical energy);
  - Projected for deployment in 2005–2006.

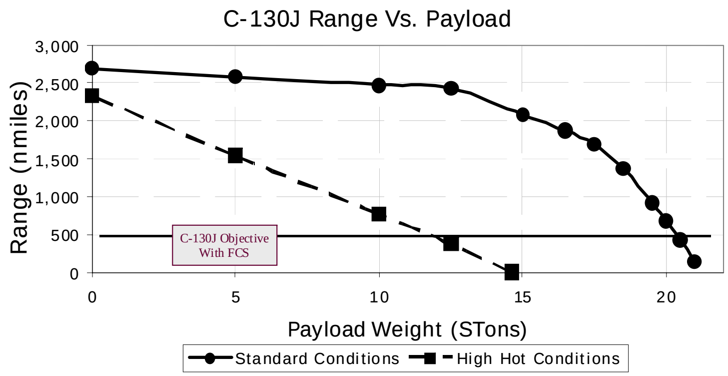
It is unlikely that an effective active protection system will be developed against kinetic-energy weapons with velocities over 1,000 m/s due to:

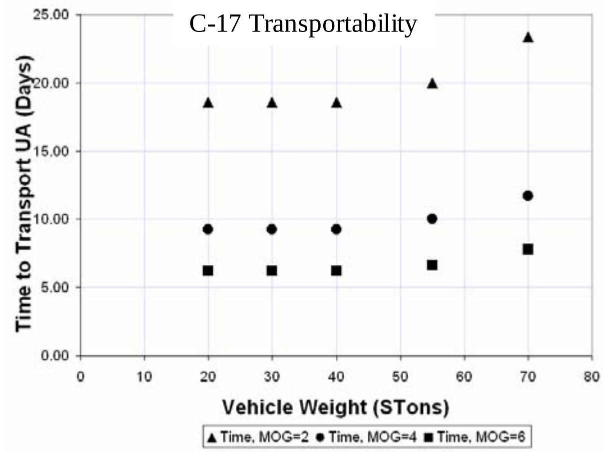
- **Time lines needed between required detection and hit are too short.**
- **Small exploitable munition signatures.**
- **Robust (difficult to disrupt) kinetic-energy kill mechanism.**

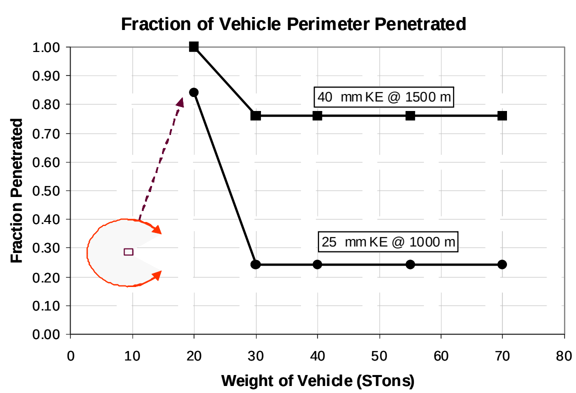
The chart gives summaries of the two active protection systems—the Russian-built Arena (state of the art) and the active protection system under development in the United States (FCLASS). Both Arena and FCLASS provide protection from projectiles with velocities below 1,000 m/s (CE rounds, antitank guided missile, rocket-propelled grenades, etc.). Because of the high velocity of kinetic-energy munitions (in excess of 1,200 m/s), it is unlikely that an active protection system against these weapons will be developed in the near future. In our vehicle survivability analysis, we therefore assumed that no active protection system will be available to protect the vehicle against kinetic-energy threats and that the amount of available kinetic-energy protection correlates with the vehicle weight.[11]

11 Ibid.

Vehicle Weight: Survivability and Transportability







- C-130 transportability implies vehicle weight less than 12 short tons.
- C-17 transportability is insensitive to vehicle weight less than 45 short tons.
- Vehicle survivability against kinetic-energy weapons implies vehicle weight greater than 30 short tons.

This chart summarizes the effect of vehicle weight on its survivability and Unit of Action transportability. These data show that the best combinations of survivability and Unit of Action transportability are achieved for vehicles in the range of 35 to 45 short tons. These vehicles offer significantly more protection than those weighing 20 short tons, without greatly affecting Unit of Action transportability. The chart on the upper left points out an additional consideration: The 20 short ton vehicle can only be transported by C-130 over a relatively short range. Thus, it has transportation limitations similar to heavier vehicles and inferior survivability.

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Summary

- C-130 transportability—a design *constraint*.
  - Vehicle design is at the "edge" of C-130 compatibility.
  - Transportability is not significantly improved.
    - Intra-theater:
      - C-130 use limited in realistic conditions;
      - C-17 insensitive to vehicle weight;
      - TSV/road transport often faster.
    - Inter-theater:
      - Air deployability of Unit of Action is cube limited for vehicles less than 35 short tons; vehicle weight is irrelevant in this region.
- Vulnerability to medium-caliber kinetic-energy weapons is greatly increased by C-130 constraint.

In the context of the desired performance of many of the Future Combat System vehicles, especially the Mounted Combat System, Non-Line-of-Sight Cannon, and the Infantry Carrier, C-130 transportability is a design constraint rather than a goal or feature. That is, because these vehicle designs would have reduced capabilities even at weights several tons in excess of what a C-130 can carry, they have been designed to the limit of the C-130 capacity.

The goal is improved transportability, but we find that intra-theater transportability is not significantly improved. Air Force planning factors are for approximately 12 tons per load with a C-130. We find that for Army high-hot operation, a 12 ton takeoff load allows for a 250 nmi one-way transit. When units, rather than single vehicles are considered, water or road transport is often faster. This (surprising to some) result is a consequence of airfield bottlenecks.

Inter-theater deployability is limited by volume rather than weight for vehicles in the 20 (or even 30) ton weight class. Vehicle weight is nearly irrelevant in this region.

None of this is to deny that from a transportability perspective lighter is preferable: Fuel efficiency on the ground and in the air is better for lighter vehicles, all else being equal. Trafficability, particularly in regions with poorly developed infrastructure, will be improved with reduced weight. However, there is no significant improvement that results from C-130 compatibility.

As we have shown for the widely proliferated 25 and 40 mm weapons, vulnerability is significantly increased by the weight constraints of the C-130.

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III. Sustainability and Reliability

Operational availability is a measure of the Key Performance Parameter.

High reliability is a derived requirement.

Prognostics is a Critical Technology.

Water generation is also a Critical Technology.

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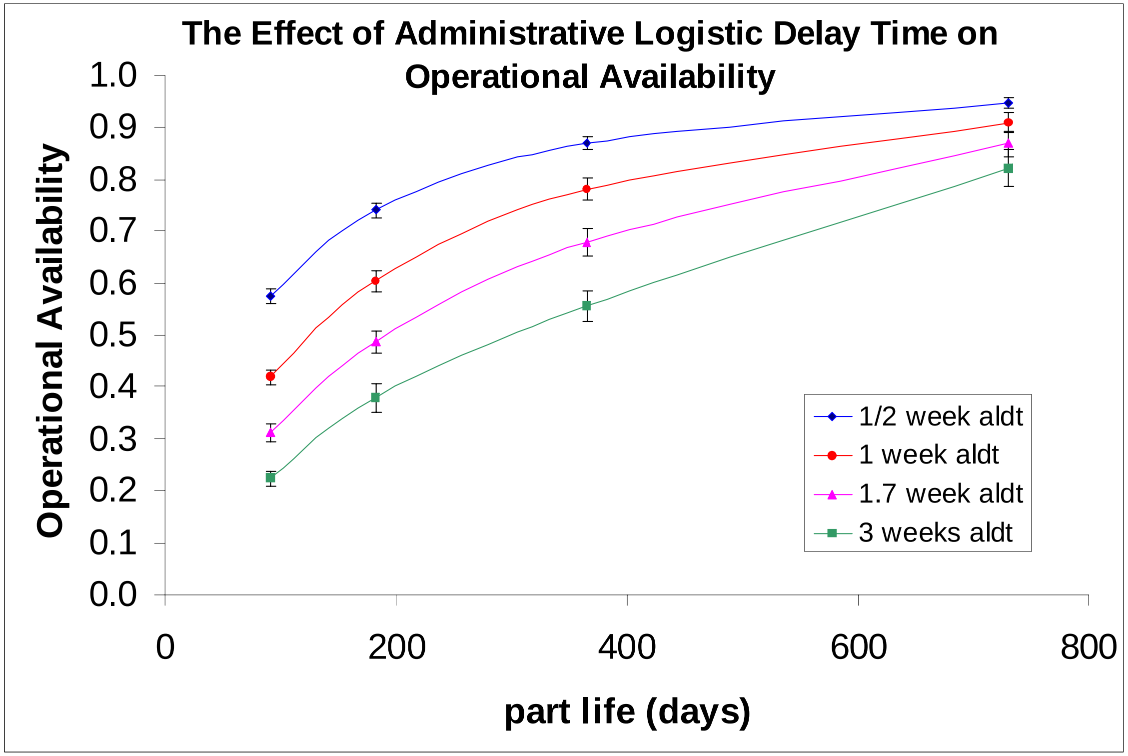
Effect of Logistic and Administrative Delay Times on Operational Availability



Improving administrative logistic delay time, that is, making spare parts delivery and distribution more effective, results in significant improvement of operational availability; the effect is especially significant when component reliability is lower.

One of the major objectives of the Future Combat System family of military vehicles is to achieve high reliability and operational availability. High reliability may be achieved by making the component parts of the system more reliable or by reducing the number of critical parts (critical parts are those that, when they fail, cause the system to abort). The risks associated with either approach are high. The Future Combat System proposed means of achieving high reliability and operation availability is a prognostics-based approach to maintenance. That is, based on the prediction of remaining life, parts vulnerable to failure are replaced just before they fail or before an upcoming mission.

In this first chart we consider the case where parts are replaced as they fail and plot the operational availability, Ao = (time vehicle is up and running) / (time vehicle is up + time vehicle is down), as a function of the reliability or lifetime of the critical parts. The time that the vehicle is down is also referred to as administrative logistic delay time. Administrative logistic delay time includes not only the time it takes to repair the vehicle, but also the time it takes to have the required parts delivered to the maintenance crew. Operational availability is plotted with four different choices of administrative logistic delay time: 1/2 week, 1 week, 1.7 weeks, and 3 weeks.

This chart is the result of a simulation[12] specifically designed to study operational availability. We made the following assumptions:

- There are 300 platforms (roughly the number of Future Combat System platforms), each composed of 20 critical parts causing a system abort if one or more parts fail.
- Average values and distributions for part lifetimes, repair times, and delivery times are extracted from field exercise and operational test data of current vehicles such as Abrams, Bradley, and Stryker.[13]
- These values are then randomly sampled as parts fail and are replaced.
- Part lifetimes are varied from 3 months to 2 years, and administrative logistic delay times are varied from 4 days to 3 weeks.

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12 P. Koehn, J. Macheret, D. Sparrow, "Improving Reliability and Operational Availability of Military Systems" (Alexandria, Va.: Institute for Defense Analyses, July 2004), IDA Document D-3006.

13 "Diagnosing the Army's Equipment Readiness: The Equipment Downtime Analyzer," RAND Report # MR-1481-A, 2002.

- Total operational period is 2 years.
- As parts fail, they are replaced as needed. We did not employ strategies using prognostics, opportunistic fix/replacement, or mass replacement of parts with a fixed time interval.

The resulting plot shows that for a given administrative logistic delay time, the operational availability increases as the reliability of the critical parts that make up the vehicle increases. This is expected. For a given critical part reliability, decreasing the administrative logistic delay time increases the operational availability. This effect is much more substantial for less reliable parts. While we accept that reducing logistic delay times could be difficult and that there can be substantial increases in administrative logistic delay times during times of high operational tempo, the values of administrative logistic delay time depicted in this chart are taken from Army data. Although it is not on this chart, the simulation shows that as the number of critical parts decreases, the operational availability substantially increases. Again, this is an expected result.

Without making any improvements in the vehicle, the operational availability can be greatly improved by making spare parts delivery and distribution more effective.

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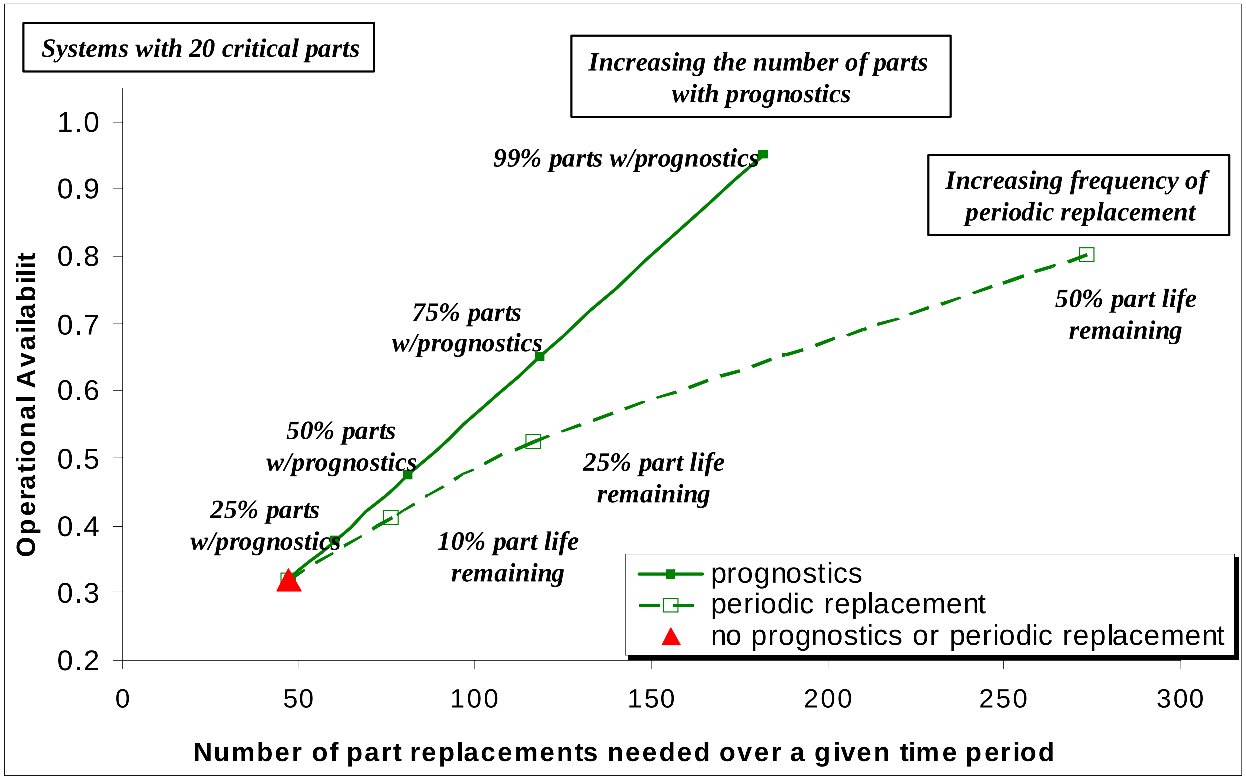
Effect of Prognostics and Periodic Critical Part Replacement on Operational Availability



Prognostics and periodic replacement maintenance strategies can be used to improve operational availability. Prognostics is more effective in terms of reducing the gross numbers of replacement parts. In either case, for systems with low reliability, a large number of spare parts are needed to maintain high operational availability.

This plot shows the effect of prognostics and periodic critical part replacement on operational availability. Two maintenance strategies are employed, prognostics and periodic replacement of all critical parts at regular intervals.

There are two curves in this chart:

- The solid curve is the operational availability with prognostics: Ao increases as the fraction of critical parts that contain prognostics is increased from 0%, 25%, 75%, and 99%.
- The dashed curve is the operational availability with periodic replacement: Ao increases as the replacement time for critical parts is increased from 0% of the part's useful life left to 10%, 25%, and 50%.

The administrative logistic delay time is held constant in this run of the simulation. In this case, the lifetime of the critical parts is ¼ year, but the monitoring time over which the operational availability is calculated is 2 years. This system is composed of 20 critical parts. Note that if the monitoring time period is long enough and the part life short enough, the system will eventually need to have all its parts replaced many times over!

This chart was produced by the simulation used for the previous chart. We made the following assumptions:

- There are 300 platforms, each composed of 20 critical parts, defined as those that cause a system abort if one or more fails.
- Average values and distributions for part lifetimes, repair times, and delivery times are extracted from field exercise and operational test data of current vehicles, such as Abrams, Bradley, and Stryker. These are the same values as used in the previous chart.
- These values are then randomly sampled as parts fail and are replaced.
- Part lifetimes are varied from 3 months to 2 years, and administrative logistic delay times are varied from 4 days to 3 weeks.
- Total operational period is 2 years.

This chart shows that both maintenance strategies are capable of producing very high operational availabilities. A follow-up question could be: Which costs more? One measure of cost is related to the number of parts that are required. By this measure, the prognostics strategy is significantly better because fewer parts are required to achieve the same operational

availability. Furthermore, as the reliability of the critical part worsens, the number of replacement parts needed grows substantially. Of course, another measure of cost is the manpower needed to perform the repairs/replacement. That is not considered in this chart, but is also a key factor in assessing maintenance strategies.

Both prognostics and periodic-replacement maintenance strategies can be used to improve operational availability. The prognostics strategy is more effective in terms of the gross number of needed parts. In either case, for systems with low reliability, a large number of spare parts are needed.

Effect of Prognostics and Periodic Critical Part Replacement on Operational Availability

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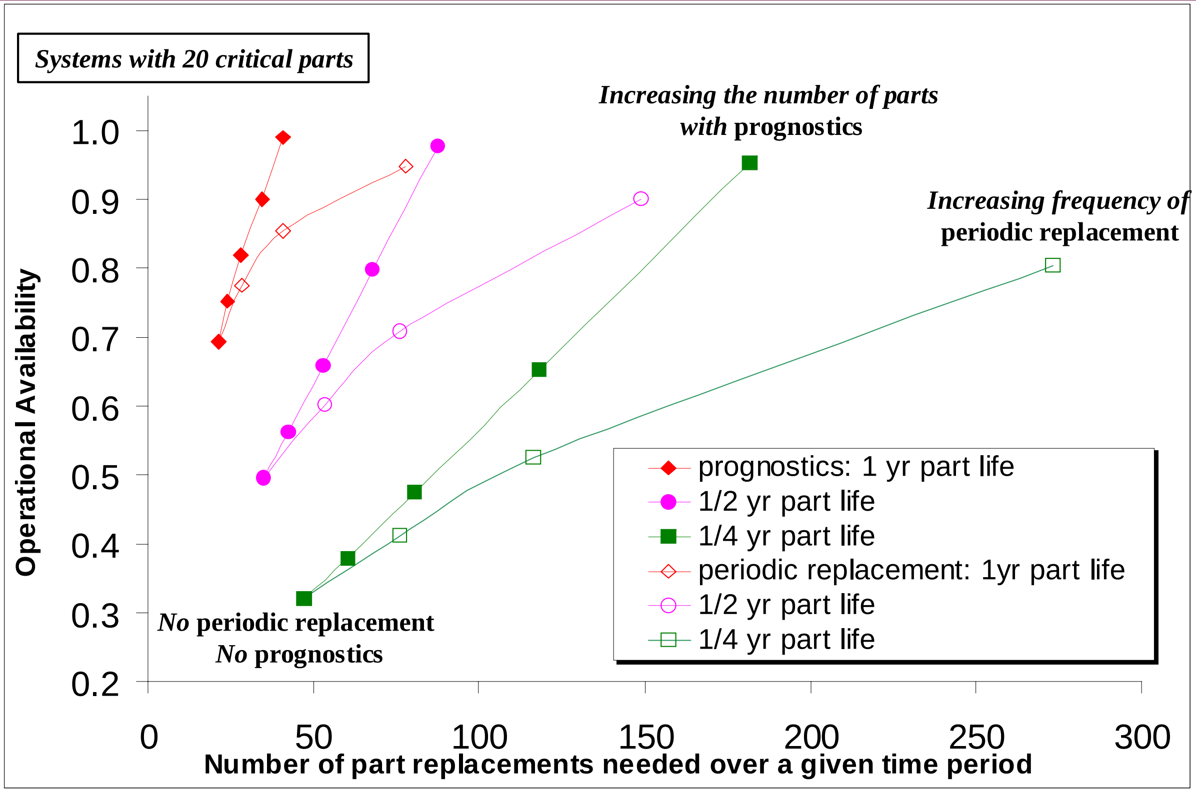

Prognostics and periodic replacement maintenance strategies can be used to improve operational availability. The prognostics strategy is more effective in terms of minimizing the gross number of replacement parts needed. In either case, for systems with low reliability, a large number of spare parts are needed to maintain high operational availability.

This chart shows the effect of prognostics and periodic critical part replacement maintenance strategies on operational availability, but also looks at this effect in terms of part lifetime. The simulation described above was used to generate this chart.

This chart has six curves, three with solid points and three with open points.

- The three curves with solid points show the results for operational availability as a function of number of needed replacement parts as the percentage of parts monitored by prognostics is increased from 0% to 100% for three different part lifetimes (1/4 year, 1/2 year, and 1 year).
- The three curves with open points show the operational availability as a function of the number of needed replacement parts as the time between replacing all critical parts in the vehicle is decreased from the full part lifetime to one-half the part lifetime for three different part lifetimes (1/4 year, 1/2 year, and 1 year).
- The administrative logistic delay time is held constant in all cases.
- Each of the 300 platforms is composed of 20 critical parts.

Again, both prognostics and full part replacement maintenance strategies can be used to improve operational availability. However, in this case, although the prognostics strategy is more effective in terms of the gross number of needed parts, as the reliability of the parts in the system gets better (i.e., part lifetimes get longer), the difference in the number of replacement parts needed for each strategy is significantly diminished.

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Operational Availability Summary

- The Future Combat System program has focused on increasing reliability to improve operational availability.
- The reduction of administrative logistic delay time complements improved reliability.
- The use of prognostics may help more with administrative logistic delay time than with reliability.
  - "Statistical" prognostics is essentially a nonmateriel solution comparable in performance to "predictive" prognostics.

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Water Generation from Diesel Exhaust

Motivation

- Understand the implications of the water generation portion of the KPP5 requirement:

  FCS FoS must incorporate an embedded potable water generation, purification, replenishment and on-board storage capability that allows the FCS and assigned crew to operate without external water re-supply for a period of 3 days high intensity or 7 days low intensity operations. (Threshold)

- Water distribution is projected to be 30 to 40% of the Objective Force daily sustainment weight requirement ([1198] ORD Paragraph Annex F 2.0.6.3.7.).
- For this study, we only considered the minimum hydration needs for the soldier.

Water Generation Parameters

- **1 gallon of diesel fuel burned produces about 0.5 gal of potable water.**
  - Theoretically, 1 gal of diesel fuel will yield 1 gal of water; about half of that is recovered after filtering and purification. The water quality meets or exceeds EPA standards.
  - Technology is TRL 5-6. Current prototype system (recovery plus storage) fits in two wheel wells of an HMMWV.
- **All manned vehicles assumed to be equipped for water generation.**
  - Vehicle variants and count taken from Family of Systems for calendar year 2012.
- **Mission Duty Cycle.**
  - The amount of fuel burned is dependent on the relative amounts of time the vehicle spends rolling, idling, and quiet (engine off); the distance traveled; and type of terrain.
- **Water generated = fuel burned × water recovery efficiency.**

Water is a major portion of the sustainment requirement.[14] Generating water to mitigate the amount that would have to be trucked in—or even becoming self-sustaining—is desirable. We wanted to determine whether or not it would be theoretically possible for a Unit of Action to be self-sustaining by using water condensed, filtered, and purified from diesel exhaust. If the Unit of Action could not be self-sustaining, to what degree would this water-generating technology advance it toward self-sustainment?

The technology to condense water from diesel exhaust is reasonably mature. The Program Manager's maturity rating (at the time of this analysis in 2003) is Technology Readiness Level 5–6.[15] The Independent Review Team at the Future Combat System Science and Technology Integrated Product Team agreed with this assessment.[16] Dr. Jay Dusenbury, who leads the joint government/civilian project team, described the successful demonstration of this technology installed on a high mobility multipurpose wheeled vehicle (HMMWV or Humvee). The water generated met Environmental Protection Agency standards for safety and "tasted good."[17]

How the technology works: When water is needed, a switch is flipped, and the water-generation system shuts off the total exhaust flow that's coming out of the vehicle and channels it into the back half of the vehicle, where it goes into a recuperative heat exchanger, chiller, and evaporator, which condenses the exhaust into liquid form. The water is then transferred to a 1 liter tank. Once the tank fills, a pump sends the water to be purified, where it goes through particulate, carbon, and ion-exchange resin filters. From there, the water goes into a storage tank, where it is disinfected using a brine solution and a Miox generator that produces hyper chloride, which will disinfect the water to 0.5 parts per million.

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14 KPP5 sustainability/reliability critical technology 22: [1198] ORD Paragraph Annex F 2.0.6.3.7.

15 Dr. Larry Delaney, Chair, Independent Review Team, "Independent Review of Technology Maturity Assessment for Future Combat Systems Increment 1," 3 Marach 2003.

16 Ibid.

17 James S. Dusenbury et. al., "Water Recovery from Diesel Exhaust," TACOM/TARDEC; water-generation parameters from personal communication with J.S. Dusenbury

For this analysis we assumed all manned Unit of Action vehicles could generate water. The efficiency with which water could be generated was taken to be 0.50: 1 gallon of diesel full burned yields 0.5 gallons of potable water, which seemed to be a reasonable starting point based upon conversations with Dr. Dusenbury (test results have consistently shown that 50 to 60% of the theoretically available water can be recovered). The mission-duty cycle tells us how the vehicles were used—how fast they were traveling, over what terrain, what fraction of time they spent idling, etc. We used mission-duty cycles based on the Stryker Millennium Challenge 2002 exercise.

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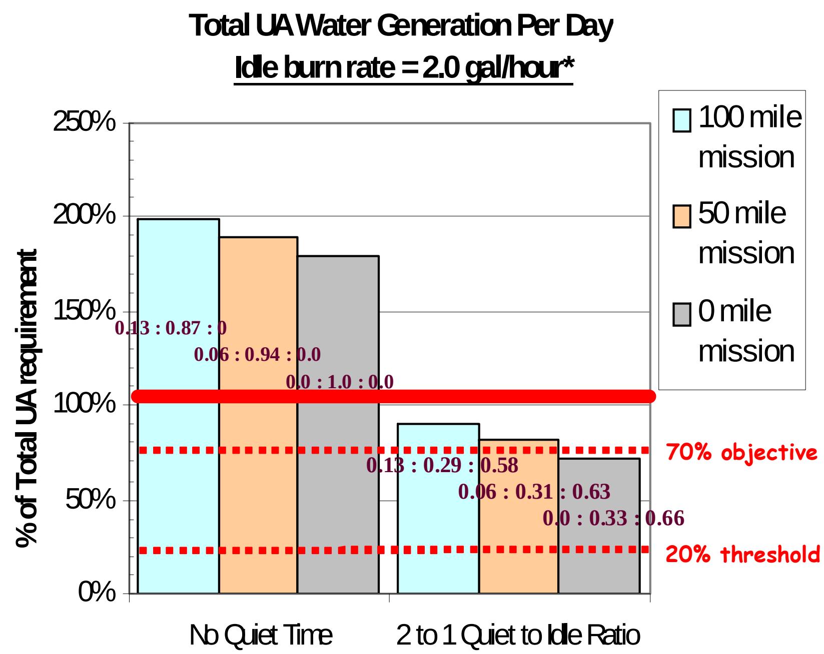
Water Generation for the Unit of Action

- Vehicle fuel efficiencies and ranges are based on Stryker:
  - Millennium Challenge Exercise 2002.
- Idle fuel burn rate assumes a Stryker-like vehicle @ 2 gal/hour.
  - A typical diesel engine idles at ~ 1 gal/hour.
  - 5.3 gal/hour (based on Future Truck Tactical System study).
    - Substantial vehicle power draw (~ 48 kW).
- Minimum Water required = 4.1 gal/soldier/day.
  - Other estimates give range of 3–7 gal/soldier/day.
  - If one includes field hospital, kitchen, laundry, maintenance, etc.…this number increases to 15.5 gal/soldier/day.
  - Unit of Action requires 2,540 × 4.1 gal/day = 10,414 gal/day (~ 43 short tons/day).



Mission Duty Cycle Time
rolling : idling : engine off
* Stryker-like vehicle

Cannot realistically satisfy Unit of Action minimum hydration requirement.

This chart describes the theoretical amount of water generated per day by the Future Combat System Unit of Action when the idle burn rate for each vehicle is 2.0 gallons/hour and the mission-duty cycle for the vehicles is similar to that of the Stryker Millennium Challenge 2002 exercise. The *y* axis is the fraction of the Future Combat System Unit of Action minimum water requirement that is satisfied over a 24-hour mission period. The *x* axis is the amount of quiet time, the amount of time the engine is off during missions of 0, 50, and 100 miles.

No quiet time means the engine always runs—the vehicle is rolling or idling. No quiet time is the maximum amount of idling. The minimum idle time is a 2:1 quiet-to-idle ratio, in which the engine is off twice as long as it idles. This plot shows that if the engines are always running with a rather high idle burn rate, enough water could in principle be produced for the Unit of Action to satisfy minimum hydration requirements. Conversely, when running the engine at a more realistic 2:1 quiet-to-idle ratio, the minimum hydration requirements cannot be met; however, it still may be possible to generate a substantial amount—around 70% of the hydration requirement. In the mission-duty-cycle scenarios in this analysis, we determined that the engine running time or idle time, not the rolling mileage, dominates the amount of water produced. Note that the number of soldiers in vehicles is 1,882; the entire Unit of Action is assumed to be 2,500. To get water generation amounts for manned vehicles only, just scale: 2,500/1,882, or approximately 1.32.

What about distribution within the Unit of Action, and is it worth it? High-occupancy vehicles like the Infantry Combat Vehicle will not produce enough water to be self-sustaining, but the low-occupancy vehicles will produce more than what is needed. Three questions arise.

1. How can that surplus be transferred to the part of the Unit of Action that needs it?
2. Is the transfer of water too complicated logistically?
3. If trucks or other vehicles have to run around, leveling off water tanks, would it not be easier to just haul in the water that is needed?

What are the implications of hybrid-electric vehicles? This analysis assumed a diesel engine with an idle rate of 2 gal/hour, integrated fuel efficiency over all terrain types, and rolling fuel consumption of about 3 mi/gal. A hybrid-electric vehicle will burn less fuel for mobility, but it will also produce less water. However, part of the motivation for hybrid-electric

technology is electric power generation for anticipated computation and communication needs. This will lead to additional fuel consumption not related to mobility. These implications illustrate the interplay among critical technologies: The gains produced by one technology may offset or counteract the gains produced by others.

The Future Combat System vehicles are weight challenged. Is the need for on-board water generation worth the additional weight cost that system adds to the vehicle? (At the time of writing, March 2003, the water generation system weighed in the neighborhood of 200–300 pounds.)

IV. Backup

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IDA/STD OSD/PA&E Relationship

- Continual 15-year relationship.
- Assess technical issues with major programmatic impact.
  - Comanche signatures, Longbow stationary target capability, Chinook vibration and operation and support costs, rotary-wing weight control.
  - Advanced Field Artillery System propellant choice; Crusader weight reduction.
  - Key Performance Parameters and structure of Future Combat System program:
    - Led to identification of vehicle design drivers;
    - Emphasis on “multi-KPP” effects.

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Army Comments

- IDA Study Results:
  - For C-130 transportability, design to 11–14 tons.
  - A 20-ton vehicle is not
    - Usefully transportable; but
    - Imposes significant design compromises on survivability.
- [This is a] “Significant Observation.”

This summary frames today’s discussions.

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Future Combat System Transportability Goals

- To deploy **units** quickly, anywhere:
  - Sea lift is faster for large (Unit of Action) size units;
  - MOG generally limits deployability by air;
  - For high-MOG destinations, air fleet size limits deployability.
  - We find fastest, point-to-point time is about 8 days.
    - Other results trace to different assumptions.
- To transport vehicles by C-130:
  - Design to edge of C-130 envelope (e.g., 20 tons) does not provide useful capability;
  - Aerodynamics will prevent operations under many conditions.

Differences include weight to be deployed—some estimates use a Unit of Action weight as low as 8,000 short tons; the "pure UZ" is currently estimated at about 16,000 short tons. The associated combat support and combat service support result in an additional 8,000 short tons; associated Air Force assets would contribute another 16,000 short tons. A second issue concerns load/unload times, especially for ships.

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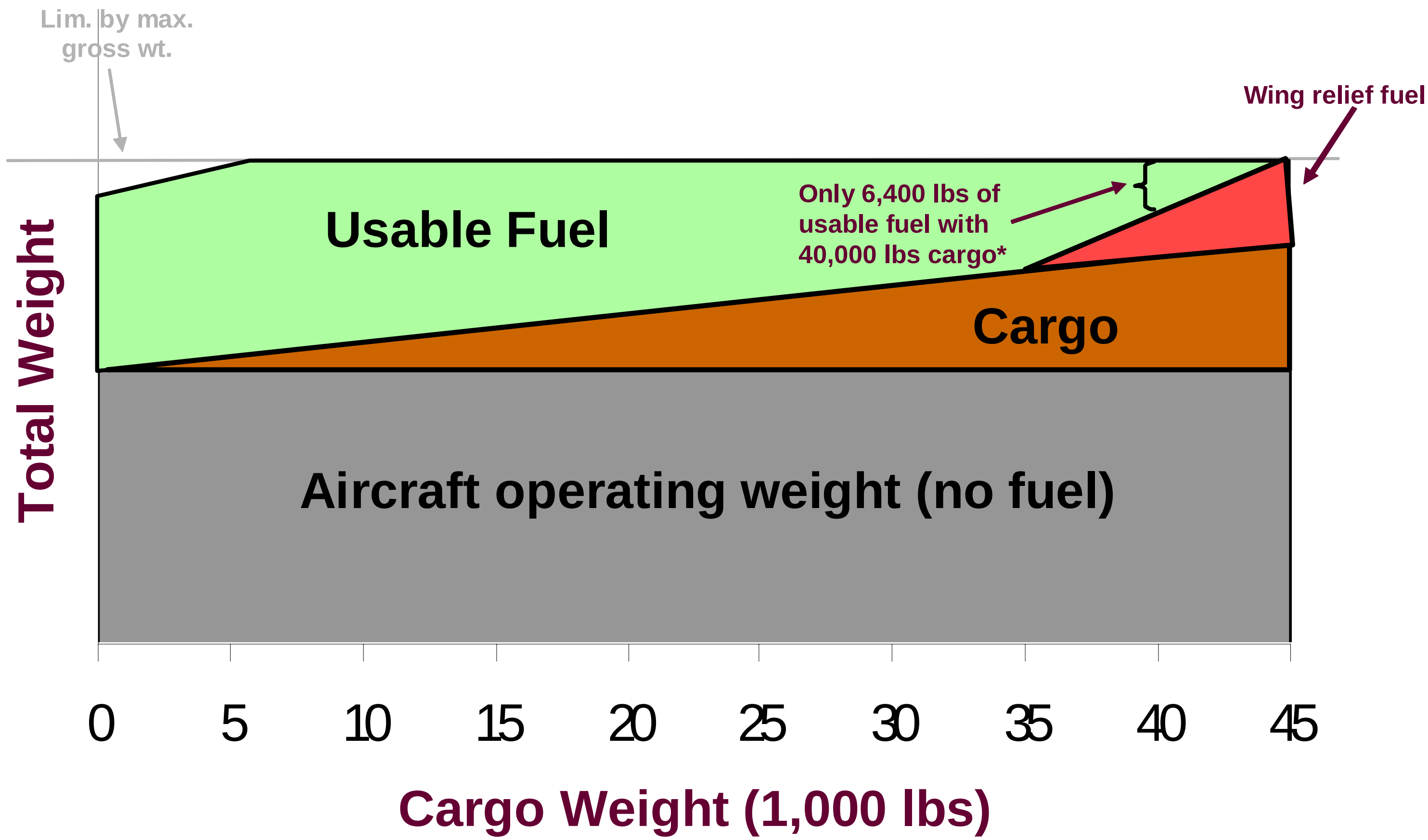
Transportability—Vehicle

- "Standard" C-130 ranges for 40,000 lb cargo:
  - C130E/H: 422 nmi
  - C130J: 679 nmi
- Caveats too numerous to detail:
  - Pressure altitude, alternate airfield, refueling capability, assault landing limits, aircraft armor weight, limitations on particular aircraft.

- Reductions in pressure altitude will limit takeoff weight compared with the “structural” ramp weight limit.
- Fuel has to be carried to permit diversion to an alternate airfield; notional amount is 3,000 lbs.
- Egress range without refueling does not permit return to base at these ranges.
- Assault landing weight is 130,000 lbs.
- Planning factor is for 1,500 lbs armor.

Loading of C-130H for Takeoff Under Standard Conditions
155,000 lb Maximum Gross Takeoff Weight*



*Based on numbers from Air Mobility Command.

This figure illustrates how a dramatic drop-off in fuel availability occurs when cargo weighs more than 35,000 lbs.

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"High-Hot" Impact on C-130J

	C-130J, "Air Force Standard"	C-130J, Army High Hot
Max. weight	155,000 lbs	125,000 lbs
Cargo	40,000 lbs	**24,000 lbs**
Usable fuel	8,350 lbs	5,610 lbs
Range	679 nmi	505 nmi

Cargo weight must be reduced to 24,000 lbs to preserve 500 nmi mile range in high-hot conditions.

Usable fuel on the high hot day is:

- 8,350 + 13,000 (wing-relief fuel) – 3,000 (minimum landing fuel) + 16,000 (reduced cargo) + 1,000 (reduced fuel to climb due to lower weight) + 250 (reduced fuel to climb due to higher takeoff altitude) – 30,000 (reduced takeoff weight).
- Scale height of atmosphere assumed to be 8 km.
- Gross takeoff weight assumed limited by lift.

(Simple physics limits here are roughly consistent with effects, noted in C-130H handbook, due to limitations from three-engine climb requirement. Simple physics underestimates effects slightly, presumably because engine performance degrades with pressure altitude for this system. We suspect this effect is countered by there being some margin at standard conditions.)

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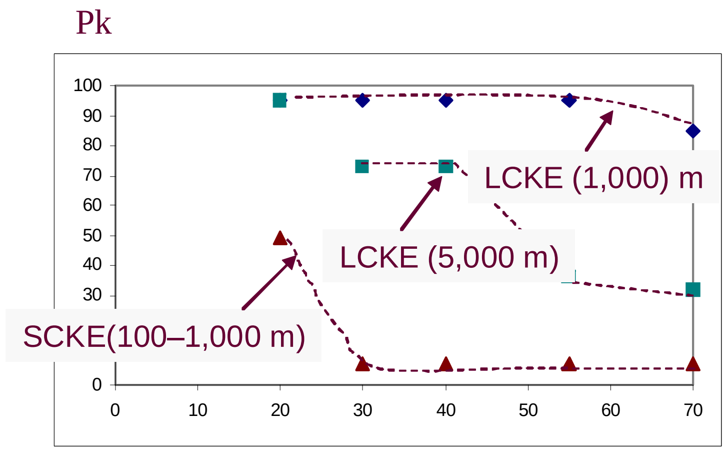
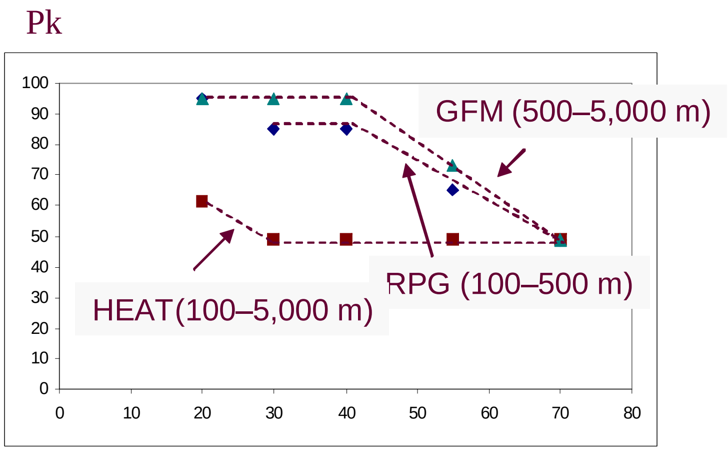
Survivability Analysis

Probability of kill (Pk) is a function of vehicle weight.





LCKE: large-caliber kinetic energy weapon
SCKE: small-caliber kinetic energy weapon

GFM: gun-fired munition
RPG: rocket-propelled grenade
HEAT: high explosive antitank missile

Lighter vehicles are especially vulnerable to SCKE and LCKE weapons.

Analysis assumptions: (1) amount of armor is specified fraction of vehicle weight, and (2) Pk calculated for direct hit.*

* W. Jackson and D. Hicks, "The Effect of Engagement Range and Vehicle Weight on Survivability," *Proceedings of the 11th Ann. Ground Target Modeling and Validation Conf.*, Michigan Tecn. University, August 2000, pp. 21–36.

ACRONYMS

AFAS	Advanced Field Artillery System
ALDT	administrative logistic delay time
Ao	operational availability
APS	active protection system
ATGM	antitank guided missile
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FCS	Future Combat System
FCLASS	Full Spectrum Close-in Shield
FTTS	Future Tactical Truck System
GFM	gun-fired munition
HEAT	high-explosive antitank
HMMWV	high-mobility multipurpose military vehicle (Humvee)
ICV	Infantry Carrier Vehicle
KPP	Key Performance Parameter
LCKE	large-caliber kinetic energy

MOG	maximum number of aircraft on ground
MTBSA	mean time before system abort
NLOS–C	Non-Line-of-Sight Cannon
O&S	operation and support
OSD	Office of the Secretary of Defense
PA&E	Program Analysis and Evaluation
Pk	probability of kill
RPG	rocket-propelled grenade
SCKE	small-caliber kinetic energy
Ston	short ton (2,000 lbs)
TACOM	Tank-Automotive and Armaments Command
TARDEC	Tank and Automotive Research, Development and Engineering Center
TRL	Technology Readiness Level
TSV	Theater Support Vessel
UA	Unit of Action

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

IDA investigated the Future Combat Systems' (FCS) Key Performance Parameters (KPPs) and their underlying Critical Technologies (CT's) to identify metrics to support Department-level monitoring of the FCS program and to gain an understanding of the implications of the KPPs (and their underlying CT's) upon the FCS program. This work focuses on the KPPs for Transportability and Sustainability/Reliability. The investigation into metrics for transportability revealed that the C130 Transportability requirement for FCS vehicles is a constraint that leads to a less survivable platform but without improving Unit of Action (UA) transportability. Further, even the transport of individual vehicles is improved only under the most favorable conditions. The FCS Sustainability/Reliability KPP aimed at improving reliability by the use of prognostics to increase operational availability. We show that the reduction of administrative logistic delay time complements the improvement of reliability and that the use of prognostics may help more with administrative logistic delay time than with reliability. Finally, we examine water generation (a CT) from fuel exhaust and show how it may affect UA sustainability.

15. SUBJECT TERMS

Future Combat Systems, Key Performance Parameters, C130 transportability, reliability, sustainability, operational availability, prognostics

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